

# Radius of Curvature Measurements

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## **An Independent Look at Accuracy Using Novel Optical Metrology**

**Second Annual MSFC Technology Days  
Mirror Development & Related Technologies**

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# Design Goals

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- Investigate measuring segment base ROC to  $\leq 1$  mm for AMSD (& NGST)
- UAH uses head-on CGH-Null segment testing and toleranced metrology/metering, so we used *a fully independent cross-check of Null viability & ROC tst'g accuracy*
- Independently configured a Prelim. New Null that works for AMSD & Verified it can be scaled/compactly-packaged to test full-sized/fast NGST Segments
- Developed a new mt'd of locating the Null that uses purely optical techniques (w/o added fixturing; though fixturing can also be used and improves results)
- Toleranced the set-up & cross-compared results with UAH (results agree to  $< 2X$ )
  - As Null WF's beat against part, Null location tol's are  $\sim$  independent of null-type
- The results show that accounting for major errors in Null location, *ROC can really be measured to  $\pm 0.71$  mm against a  $\pm 1$  mm goal.*
  - *This is a good news story! There appear to be no show-stoppers here!*

# TABLE 1

## PRELIMINARY REQUIREMENTS AND SPECIFICATIONS FOR A NULL LENS TO TEST A OFF-AXIS PARABOLA MIRROR IN CONJUNCTION WITH A CGH



<u>PARAMTER</u>	<u>REQUIRMENT</u>	<u>PERFORMANCE OF CANDIDATE NULL LENS</u>
SURFACE TO BE TESTED.		
1. TYPE	OFF-AXIS PARABOLA	SAME
2. EQUATION	SEE SMITH*, PG 484	SAME
3. RADIUS OF BEST FIT SPHERE	10000 MM	SAME (10M Worst Case Used)
4. USED APERATURE SHAPE	SPHERICAL	SAME
5. USED APERTURE RADIUS (MM)	700 MM	SAME
6. DECENTER OF USED APERTURE FROM VERTEX TO MIRROR CENTER (MM)	1400	2000 (Intentionally Pushed Off-Axis to Simulate NGST Segment)
7. MAXIMUM DEPARTURE FROM BEST FIT SPHERE (MM)	2.041	6.897 (Fully Off Axis)
NULL LENS.		
8. TYPE	A. REFRACTIVE/REFLECTIVE WITH CGH, AND	SAME
	B. ECCENTRIC APERTURE OR TILTED AND ECCENTRIC DECENTERED COMPONENTS, AND APERTURE	SAME
		(OFFNER CONFIG. IN THE ABERRATION CAUSTIC OF TEST PIECE)

\* Modern Optical Engineering, 3<sup>Rd</sup> Edition, McGraw-Hill, 2000

# TABLE 1 (CONTINUED)

## PRELIMINARY REQUIREMENTS AND SPECIFICATIONS FOR A NULL LENS TO TEST A OFF-AXIS PARABOLA MIRROR IN CONJUNCTION WITH A CGH



<u>PARAMETER</u>		<u>REQUIREMENT</u>	<u>PERFORMANCE OF CANDIDATE NULL LENS</u>
10.	MAXIMUM APERTURE DIAMETER (MM)	NOT SPECIFIED	< 152.4
11.	REFRACTIVE MATERIAL	NOT SPECIFIED	SCHOTT BK7, SF 11
12.	NUMBER OF ELEMENTS	NOT SPECIFIED	4
13.	TYPE OF ELEMENTS	NOT SPECIFIED	SPHERICAL
14.	TEST WAVELENGTH (NM)	NOT SPECIFIED	632.8
15.	MAXIMUM NORMALIZED UNCORRECTED SLOPE (WAVES PER RADIUS DOUBLEPASS @ 632.8NM)	NOT SPECIFIED	EVAL in FINAL DGN; OK (TBR)
16.	MAXIMUM RADIUS OF CURVATURE MEASUREMENT ERROR	< 1 MM	0.71 MM
17.	MAXIMUM WAVEFRONT DEGRADATION DUE TO FABRICATION AND ASSEMBLY (NULL LENS OPTICS ALONE) (RSS WAVES @ 632.8NM)	NOT SPECIFIED	TBD, NOTE 1
18.	MINIMUM ERROR ALLOCATIONS FOR FABRICATION AND ASSEMBLY	NOT SPECIFIED	TBD
19.	MAXIMUM MAPPING ERROR TO CGH	NOT SPECIFIED	TBD
20.	MAXIMUM DEVIATION BETWEEN NOMINAL AND AS-BUILT MAPPING	TBD	TBD
CGH.			
21.	INPUT BEAM	NONE	REAR OF OFFNER
22.	MAXIMUM SIZE	NONE	80 MM
23.	SPECIFICATION OF WAVEFRONT	NONE	PRIME ARCH

# AMSD Compared With NGST Primary

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## AMSD

- Base ROC = 10000 mm
- Conic Constant (k) = -1 (Parabola)
- Segment Diameter = 1400 mm (Point-to-Point)
- Mirror Center = 1300 mm Off-Axis
- Parent f/#: 1.25
- Segment f/#: 3.571

## NGST

(Yardstick\_OTA\_ver980928\_CODEV.se  
q)

- Base ROC = 20000 mm
- Conic Constant (k) = -0.998470 (Ellipsoid)
- Segment Diameter = TBD
- Mirror Center = TBD
- Parent f/#: 1.25 (TBD)
- Segment f/#: TBD

# AMSD Compared With NGST Primary (Cont.)



## AMSD

- Aspheric sag departure from base ROC: 2.041 mm \*
- Though this  $3600 \lambda_v$  has a  $\sim 316 \lambda_v/\text{mm}$  slope, it's rate of aspheric departure (difference from base ROC): 6.517 (waves/mm)
- This *is* compatible with today's microlithographically produced CGH's ( $0.25 \mu\text{m}$  spatial resolution  $\Rightarrow < 0.001 \lambda_v/\text{Pixel}$  for a 1K x 1K CCD Array)

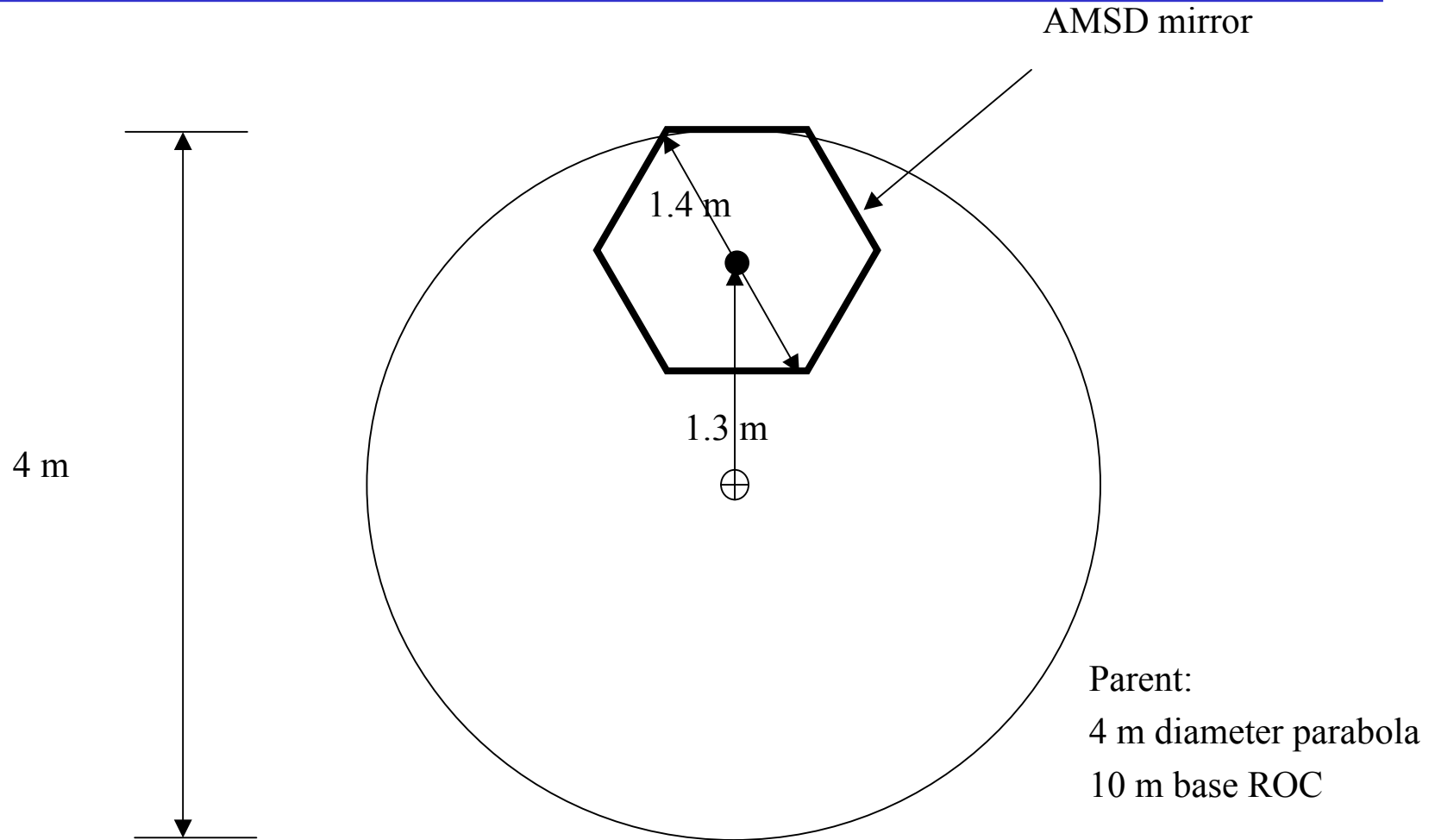
## NGST

- Aspheric sag departure from base ROC: 4.076 mm with 20M Radius \*
- Rate of aspheric departure (difference from base ROC): 6.508 (waves/mm)
- This is also fine for a CGH

\* 6.897 mm at a Very Worse Case of a 10M Radius

\* This is  $\sim 0.5$  mm from a decentered different sphere localized on the segment

# The AMSD Primary (Segment of Parent)



# We First Configured A Worst-Case Null/CGH For Use in ROC Tolerancing

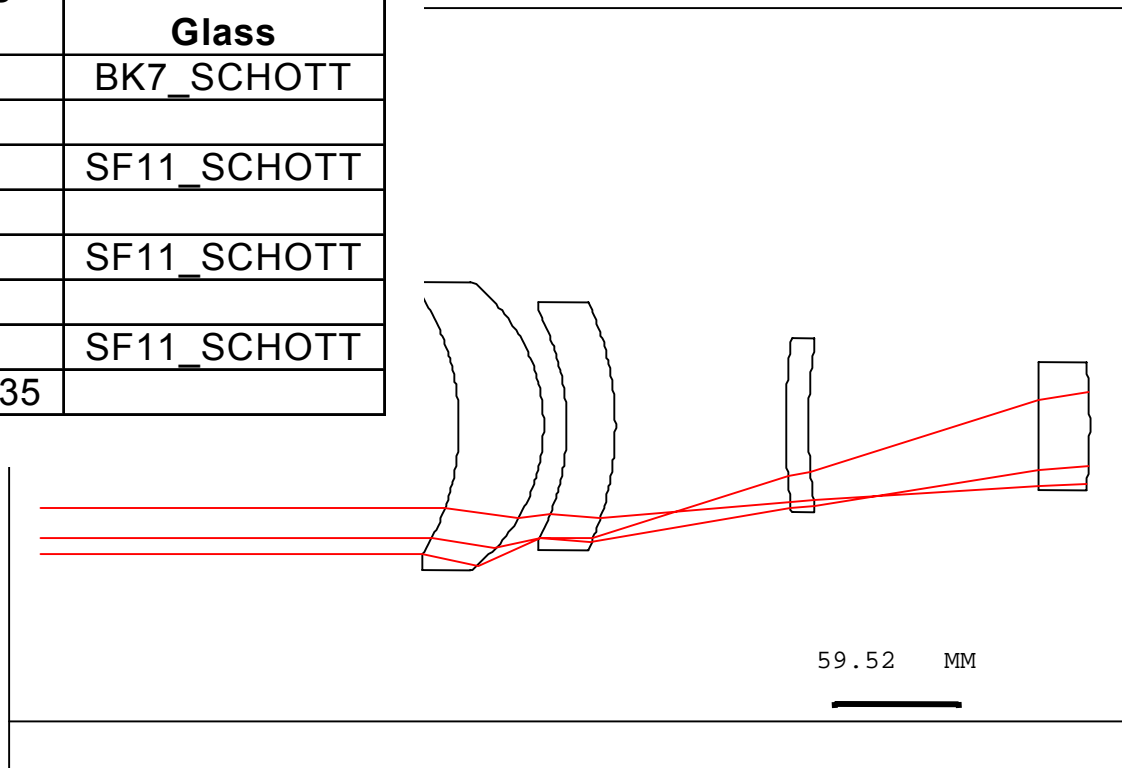
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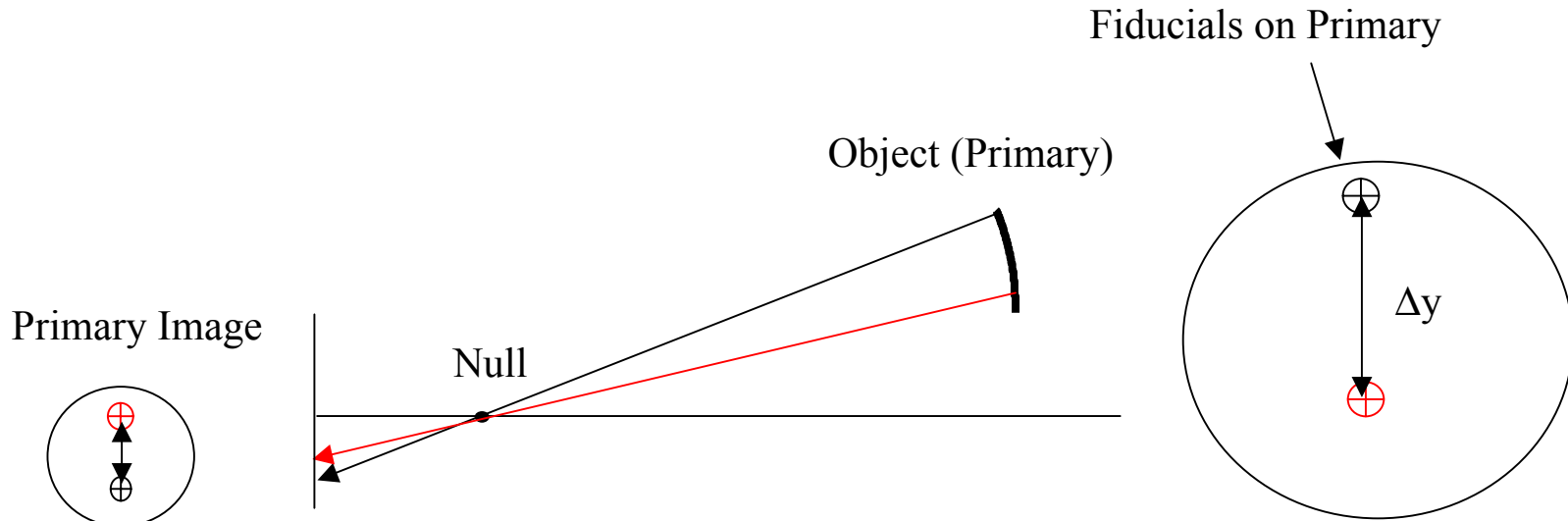
- Since NGST Vendor Architectures may have different F/No's, **we purposely pushed the design** to see if we could achieve a “small”-sized package (e.g. 6” apertures) and still get a Null that would work at F/1 Speeds
- We **successfully produced a Preliminary Design for an F/0.93 Primary** (AMSD Mirrors are F/1.25)
  - Focal Length = 5000 mm
  - Conic Constant (k) = -1 (Parabola)
  - Segment Diameter = 1400 mm (Across-Flats)
  - Mirror Center = 2000 mm Off-Axis (AMSD *Edge* is 2M Off-Axis)

# Preliminary Null Prescription

Element	Radius (mm)	Thickness (mm)	Glass
1	-119.451	40.557	BK7_SCHOTT
	-86.3283	11.04051	
2	-117.683	23.3	SF11_SCHOTT
	-141.281	81.69713	
3	327.0295	10.8091	SF11_SCHOTT
	262.36	110.3489	
4	-2489.7	24.2	SF11_SCHOTT
	-299.284	10097.916935	



# Positioning the Null with Respect to the Primary

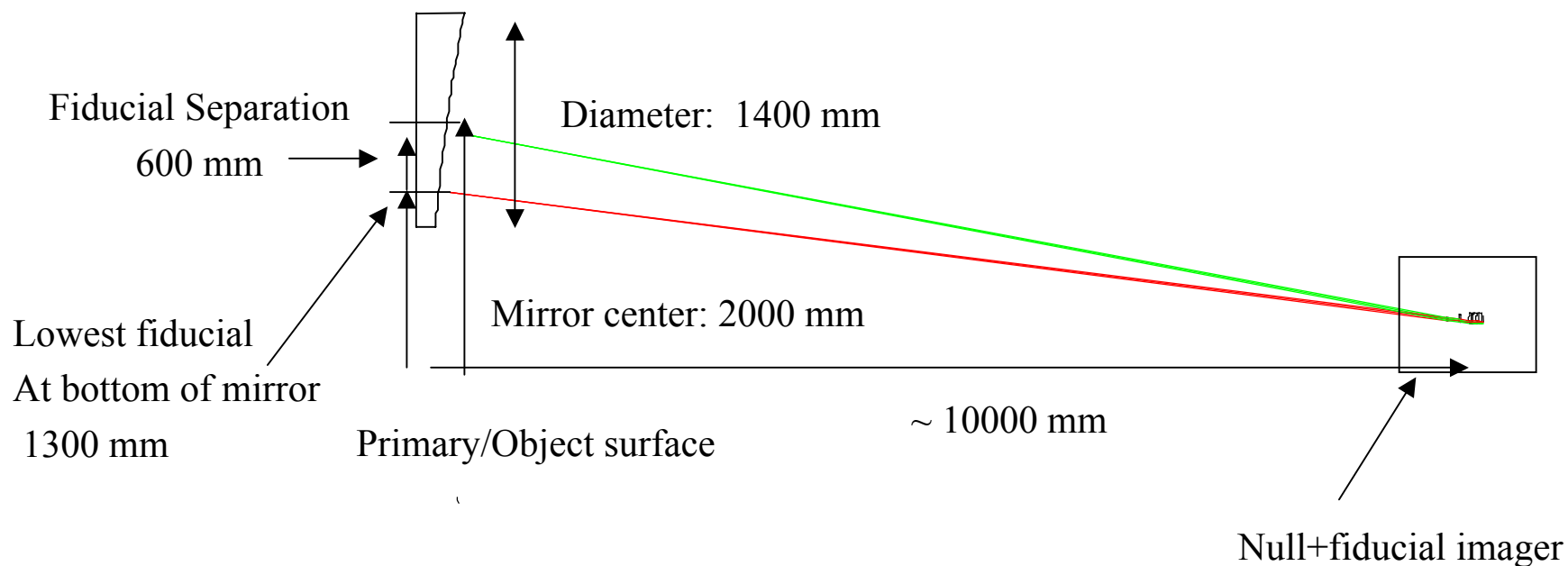


**Adjust mirror to null separation until image reaches a predefined separation.**

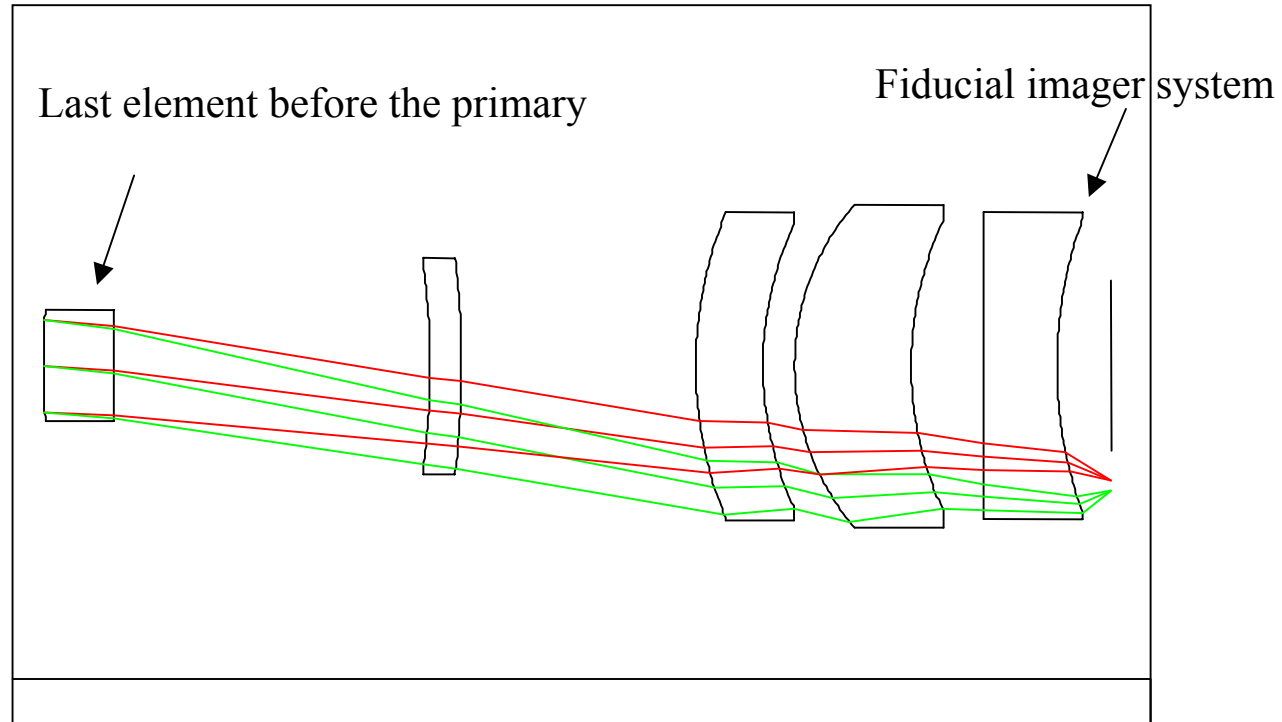
**Then we know the mirror is positioned correctly.**

# Layout for Fiducial Imaging

Try to Choose Fiducial Separation that Gives Reasonable Imagery, i.e., Smaller Fields are Easier.

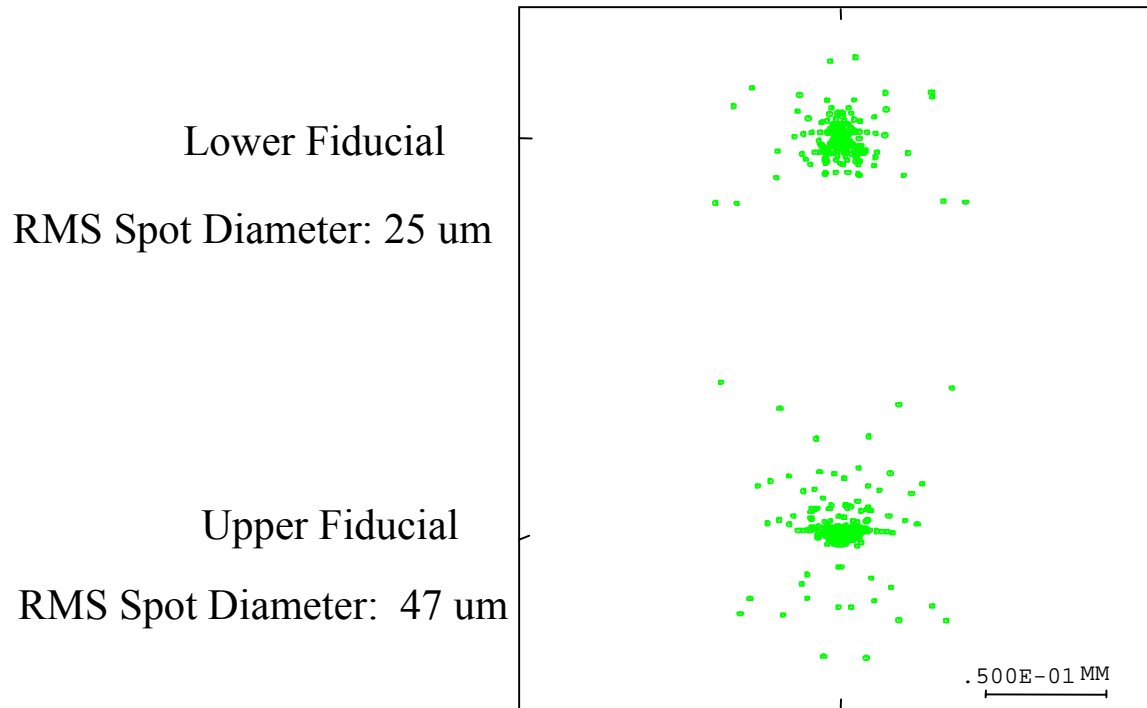


# Fiducial Imaging System – “Toy Model”



Fiducial Imager System is used only to position the primary and is then Removed to take interferograms.

# Fiducial Imaging System – Spot Diagram



- RMS Spot diameter on the order of 10 pixels for a visible camera. The number is reasonable for obtaining centroiding.

# Approach to Tolerancing the ROC Measurement

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- For nominal system, Fiducial separation at CCD is recorded
- **Fiducial Heights (e.g. Decenters), Null Lens Focal Length, and Image Plane are perturbed**
- **Mirror-to-Null spacing also toleranced** relative to ability to use expected Fiducial Image Separation as the key ingredient in setting Null-to-Primary location/distance
- **Camera Pixelization and Centroiding Error included**
- **Impact of Gravity examined**
- **Deviations are RSSed & used to estimate the error in the mirror radius of curvature**

# Inverse Null Corrector (INC) for Use in ROC Testing

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- A separate Inverse Null will eventually be desired
- Use the INC to *quantitatively* verify the Null
- Also use the INC to Monitor Null Lens Stability  
(a Lesson-Learned from HST)

# One Can Detect Changes in the ROC Through Zernikes

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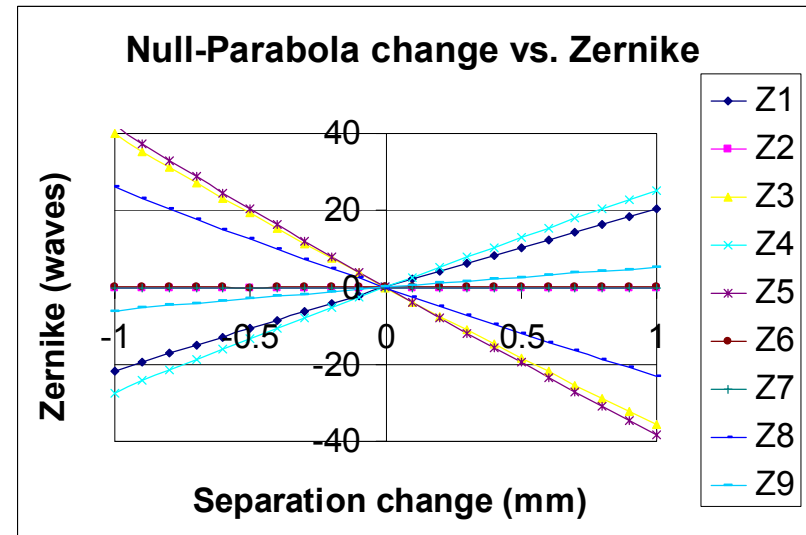
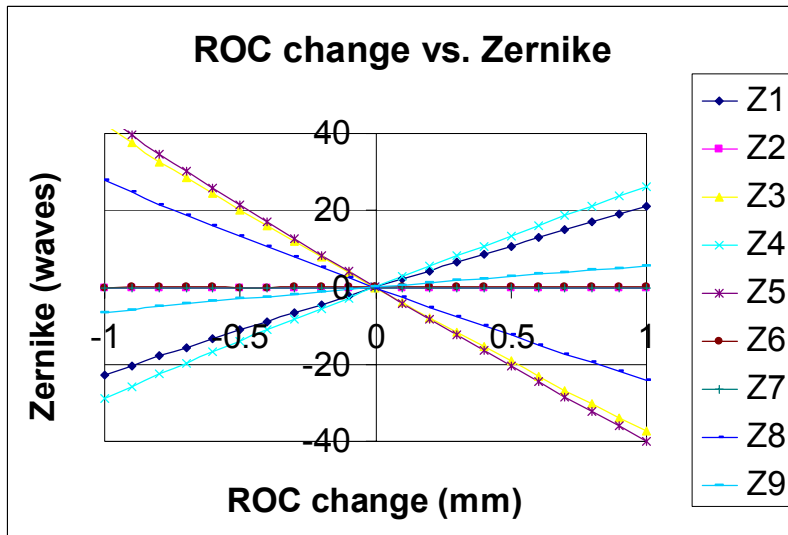
- Examine evolution in Zernikes with changes in
  - Base ROC
  - Null-Parabola separation
  - Tips/tilts and decenters
- Find that the changes are linear provided that the misalignments are not too large
- This means that the ROC change from nominal can be determined from Zernike terms

# Use of Zernikes

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- **Exit pupil is anamorphic which means:**
  - **Zernikes term are not orthogonal** (fitting more Zernike terms changes lower order terms)
  - Since the Zernike terms are not orthogonal, they can no longer be clearly associated with typically categories, i.e. fringe Zernike  $z_9$  is nominally spherical
- **However, we *are* ok** in this case:
  - Taking 36 terms vs.. 37 terms has a small effect on terms 1 – 36
  - Goal of fit is to determine how Zernikes change so that the ROC can be determined via a curve fit or look up table
- **Zernikes change in a deterministic way even though fit over elliptical pupil**

# Vary Base ROC & Null/Primary Separation (Fringe Zernikes)



Results of least square fit to data show deconvolution w/Dz difficult at best

ROC change vs.. Zernike fit

Z4 slope: 27.43035455  
waves/mm

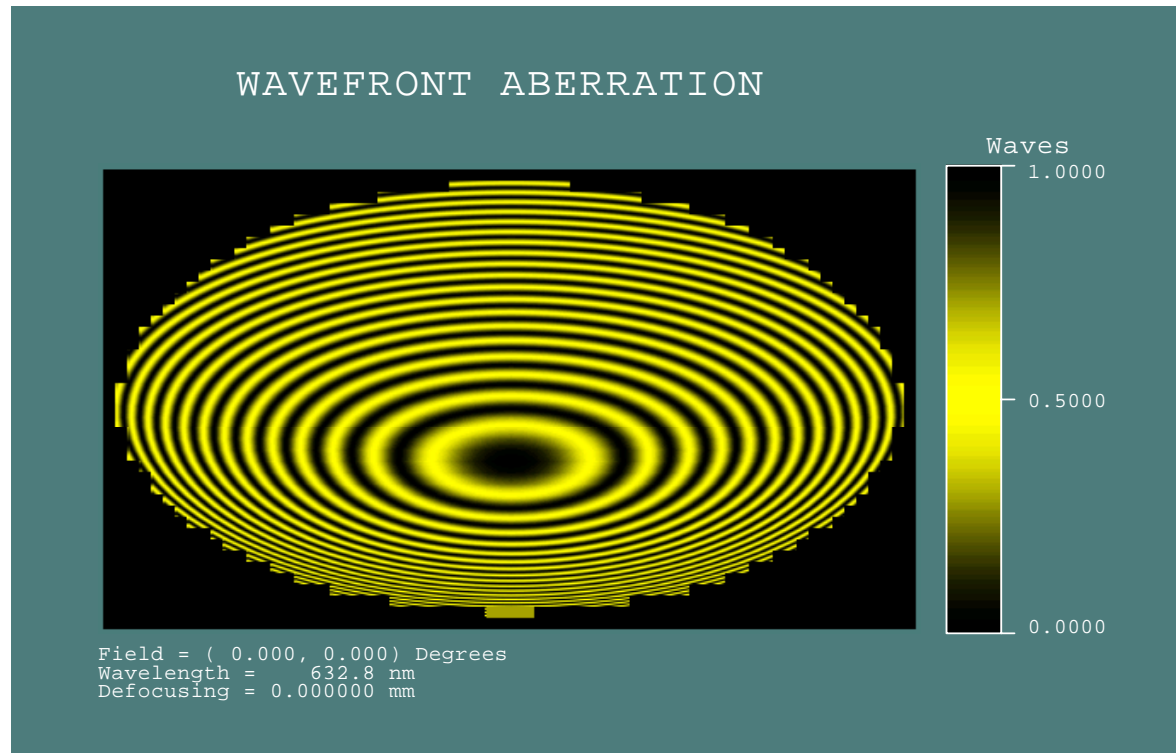
Z4 intercept: -0.39794 waves

Null-Parabola separation vs..  
Zernike fit

Z4 slope: 26.2625 waves/mm

Z4 intercept -0.34644 waves

# Interferogram for ROC Increase of 1 mm

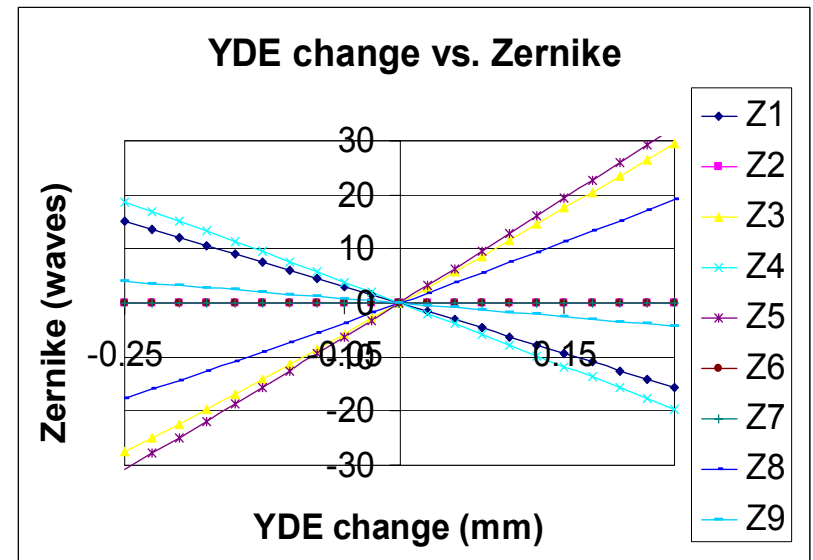
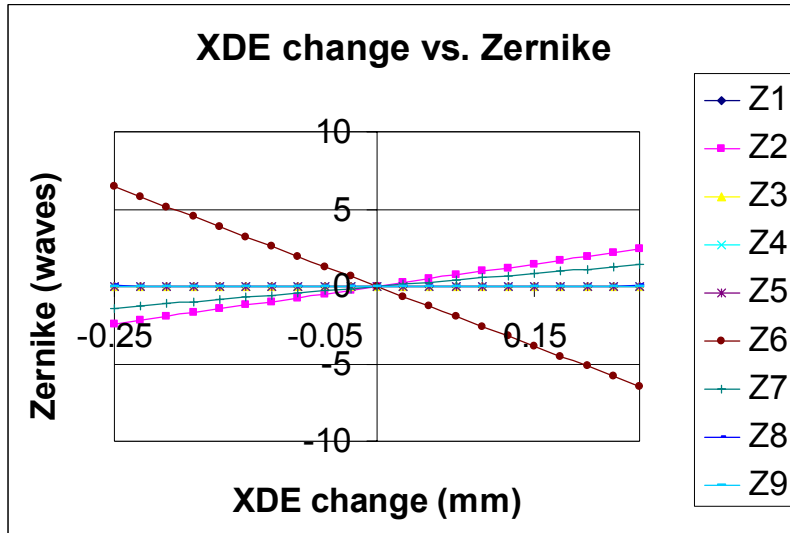


18.8 waves of aberration P-V

Can capture with an interferometer

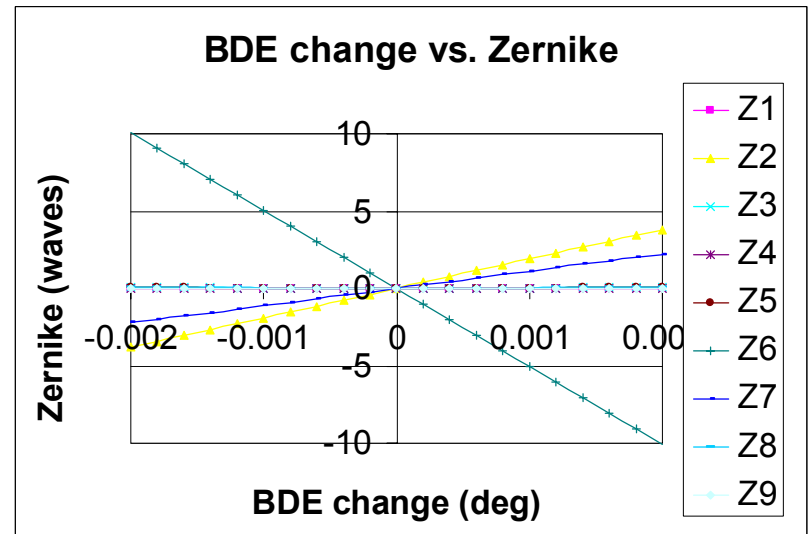
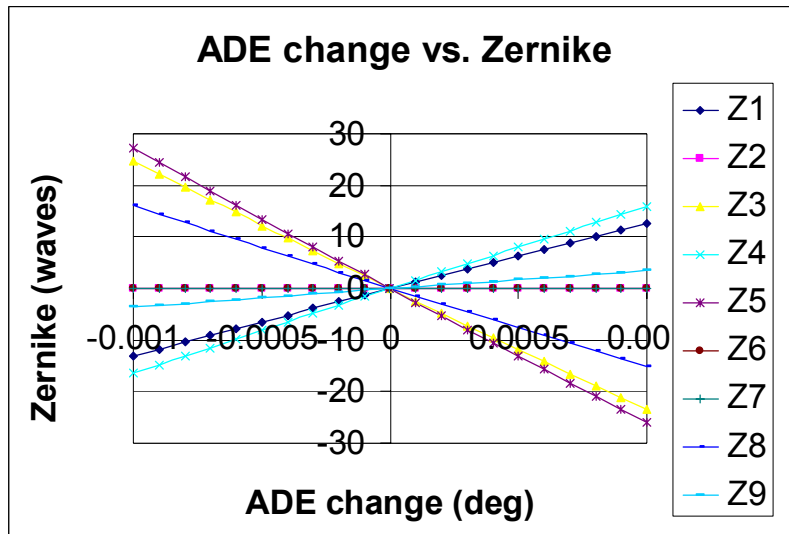
# Mirror Decenters

- Primary contribution is Z6 (astigmatism)
- Small slope on Z4, 0.0005 wave/mm
- Expect ROC measurement to be **insensitive to x-decenters**
- Large Z4 slope, 77 waves/mm
- Equivalent to 0.75 mm ROC error
- Expect ROC measurement to be **sensitive to y-decenters**



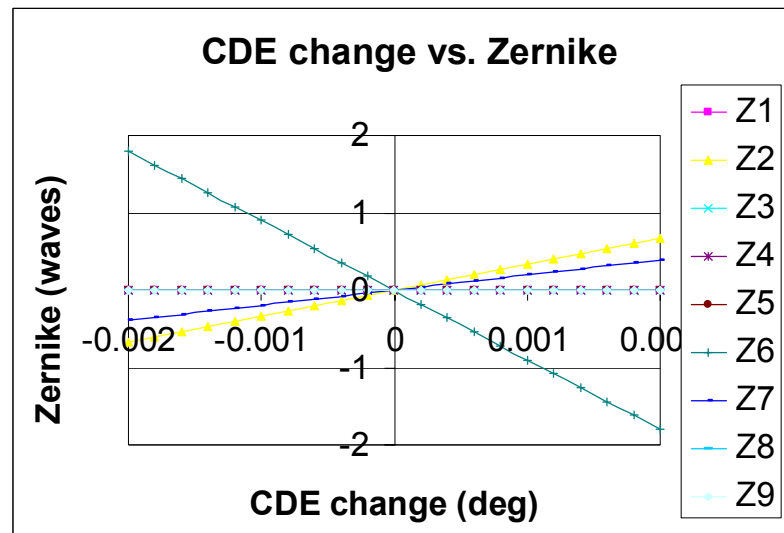
# Mirror Tilt About Local Piece-Part Center (ADE/BDE)

- Large Z4 slope, 16000 waves/deg.
- Expect ROC measurement to be **sensitive (arc-sec level) to ADE tilt** (top of segment moves toward Null)
- Primary contribution is Z6
- Small slope on Z4, 0.08 wave/deg.
- Expect ROC measurement to be **insensitive to BDE tilt**



# Mirror Tilt/Clocking (CDE)

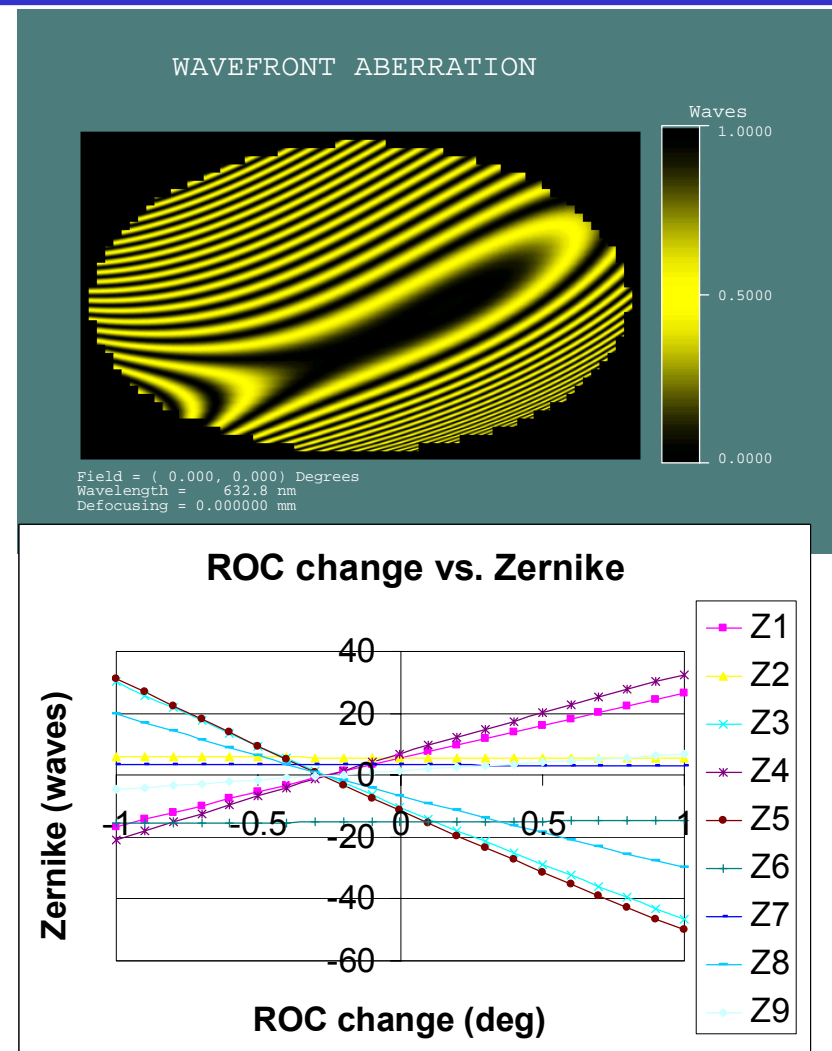
- Primary contribution is Z6
- Small slope on Z4, 0.01 wave/deg.
- Expect ROC measurement to be **insensitive to CDE tilt**



# Interferogram for an Amalgam of Tilts and Decenters

- Tilts:
  - ADE 0.0002 deg (0.72 arcseconds)
  - BDE 0.0006 deg. (2.16 arcseconds)
  - CDE 0.01 deg (36 arcseconds)
- Decenter
  - XDE 0.125 mm
  - YDE -0.05 mm (easy for Leica\*)
- **ROC error: 0.26 mm**

\* and also 36X looser than 1<sup>st</sup> cuts based on a *purely* optical technique for lateral location



# A “New” Concept for ROC Testing

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- With an appropriate test set-up, power measured in interferograms (beyond calibration tolerances) can be attributed to the Primary Segment's ROC
- We first show an inventive way to Calibrate Null Lens Power/Focal-Length
- We then show that we can use Fiducials on the Primary Mirror (with locations measured to rational accuracy) to adequately locate Null *w/o* mechanical ref.'s
- Interestingly (& importantly) use of these Fiducials to locate the Null-Lens does not not get corrupted by Segment Power
- The independent nature of Fiducial Imaging and Segment Power comes about because the Segment is located at an Object Plane where Marginal Ray Heights are zero (The influence of surface power comes about from the product of surface power and marginal rays heights; the later are zero at an Image/Pupil Plane. If this was not true, one might need self-illuminated fiducials)

# **Concentrate on Errors That Show Up as Power (Indistinguishable From ROC Err.)**



- These **errors** will be **symmetric so** that either **rotating the null** or the primary **will not remove** them
- **Use a pair (or more) of Fiducials** on the Primary and Tolerance Their Spacing (this ties to S/N, pixelization errors, etc.)
- The Fiducial Image-Separation is used to Position the Primary relative to the Null (can supplement by other mechanical measurement methods, a Leica, etc.)
- CGH can also be located conjugate to mirror's image, and it may also use Fiducials
- **We have toleranced this method and it can successfully measure mirror radius of curvature to the accuracy needed**

# One Way to Work ROC Tolerancing

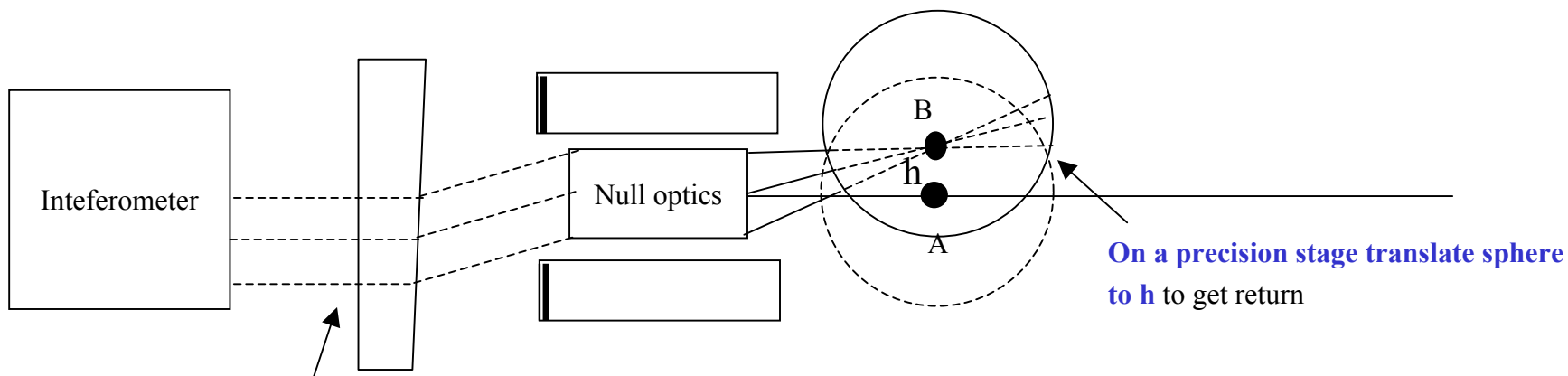
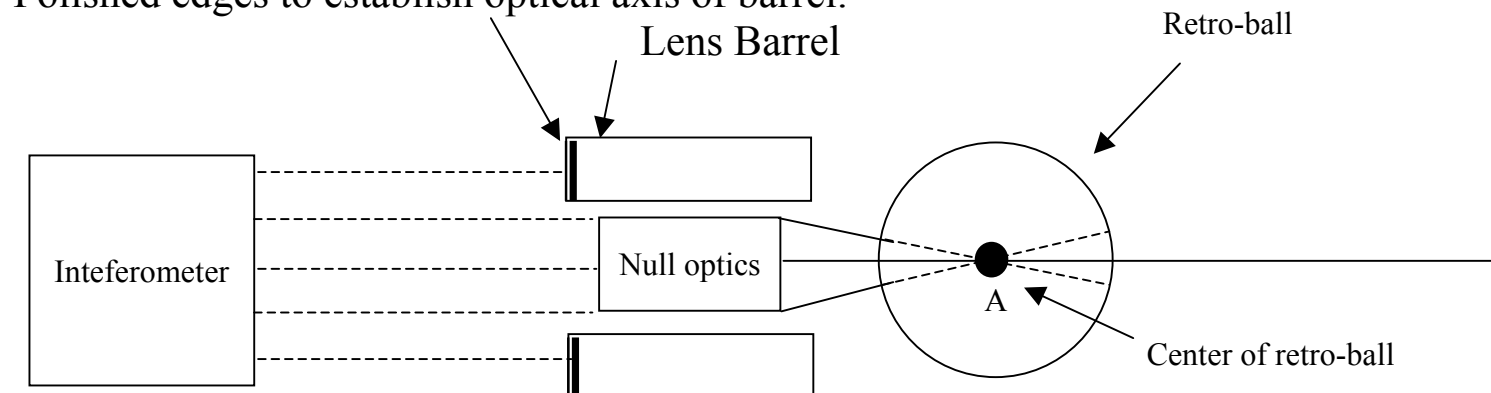
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- Tolerance Drivers can be established using fairly simple analytical models
- The Model uses information obtained from a Preliminary Null Design incorporating Null-Lens FL, Entrance Pupil Dia. & Segment-to-Null Spacing
  - Null replaced with an ideal lens, i.e. a CODE V ® Lens Module
  - Results are shown for actual AMSD Mirror Diameter and Offset
  - Results are nearly independent of AMSD mirror offset
- Examine the effect of errors on Null-to-Parabola separation
  - Focal Length
  - Fiducial image plane location
  - Fiducial separation
  - Camera pixelization/centroiding accuracy
  - Gravity

# Measure Focal Length of Null

Polished edges to establish optical axis of barrel.



Precision wedge –which deviates beam by  $\theta$  and shifts focus from A to B

**Compute FL from knowledge of shift,  $h$ , and from input beam angle,  $\theta$**

# Errors in Focal Length Measurement

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## Precision Wedge

1. Prism angle measurable to 0.5 arcseconds. Rotary table is used and calibrated against a Zygo as part of this process
2. Information from Tom Bialek President of Prism's Unlimited
3. Schott can measure index of refraction to  $10^{-6}$

## Translation Stage

Commercial translation stages good to  $0.1\text{ }\mu\text{m}$ , i.e. Newport stage

# Null Lens Focal Length Measurement -- Example

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$\theta$ : Input beam angle is 10 degrees

$h$ : Mirror shift is 25 mm

$\Delta h$ : Lateral measurement error 0.1  $\mu\text{m}$

$\Delta\theta$ : Error in wedge of 0.5 arcseconds

$$\frac{\Delta f}{f} := \sqrt{\left(\frac{\Delta h}{h}\right)^2 + \left[\Delta\theta \cdot \frac{1}{(\cos(\theta))^2 \cdot \tan(\theta)}\right]^2}$$

**Measurement of Focal Length possible to within 0.002 %**

# Impact of Meas. Error in Null FL on Primary-to-Null Lens Spacing (vs. CODE V)



- **Uncertainty in Null Focal Length**

$$\Delta \text{object\_distance} := \left( \left( \frac{\Delta \text{focal\_length}}{\text{focal\_length}^2} \cdot \text{object\_distance} \cdot \text{image\_distance} \right) \right) \cdot \left( 1 + \frac{\text{image\_distance}}{\text{object\_distance}} \right)^{-1}$$

$$\Delta \text{focal\_length} / \text{focal\_length} = 0.00005$$

$$\text{Focal\_length} = 350 \text{ mm}$$

$$\text{image\_distance} = 362 \text{ mm}$$

$$\text{Object\_distance} = 10000 \text{ mm}$$



$$\Delta \text{object\_distance} = 0.50 \text{ mm}$$

**Compares with CODE V results of 0.485 mm**

# Error in Image Plane Location Comparison with CODE Results

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- **Uncertainty in image plane location**

$\Delta\text{image\_distance} = 10 \text{ microns}$

$\text{image\_distance} = 362 \text{ mm}$

$\text{Object\_distance} = 10000 \text{ mm}$



**$\Delta\text{object\_distance} = 0.275 \text{ mm}$**

**Compare with CODE V results of 0.272 mm**

# How Blurred is the Image Plane Due to the Shift?

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Equate focal length change relation and magnification change relation and  
Re-arrange terms:

$$\text{image\_distance} = 362 \text{ mm}$$

$$\text{Object\_distance} = 10000 \text{ mm}$$

$$\Delta \text{object\_distance} = 0.50 \text{ mm} \quad (\text{determined earlier})$$



$$\Delta \text{image\_distance} = 18 \text{ um} \quad (\text{determined from } \Delta m \text{ equation})$$

**Putting in an image plane shift yields only a marginal change in the RMS spot size.**

# Error in Fiducial Separation Comparison with CODE Results

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- Uncertainty in the fiducial spacing

$$\Delta_{\text{object\_distance}} := \frac{\Delta_{\text{fiducial\_separation}}}{\text{fiducial\_separation}} \cdot \text{object\_distance}$$

$\Delta_{\text{fiducial\_separation}} = 10 \text{ microns}$

$\text{Fiducial\_separation} = 600 \text{ mm}$

$\text{Object\_distance} = 10000 \text{ mm}$



**$\Delta_{\text{object\_distance}} = 0.167 \text{ mm}$**

**Compare with CODE V results of 0.165 mm**

# Centroiding Accuracy

Equation courtesy of Paul Glenn: Bauer Associates, Inc.

- Centroiding will be used to locate the center of the Fiducials

$$\text{centroid\_error} = \frac{\sqrt{3}}{6} \cdot \left( \frac{I_{\text{noise\_floor}}}{I_{\text{average}}} \right)$$

$I_{\text{noise\_floor}}$  is the minimum readable by the camera

$I_{\text{average}}$  is the average intensity in the centroiding region

- Assume an 8 bit camera
- Assume the first bit is noisy so that  $I_{\text{noise\_floor}} = 1$
- Assume that the average intensity in the centroiding region is  $\frac{1}{2}$  saturated over the Search area, i.e.  $\frac{1}{2}$  the camera maximum or 128 out of 256

**Can centroid to 0.003 of a pixel**

# Pixelization Error

- Interferometer detector has 1000 x 1000 pixel CCD array which is imaged onto the primary with a diameter of 1,400 mm
- Height uncertainty measurement is 1.4 mm \* centroiding error

$$1.4 \text{ mm/pixel} * 0.003 \text{ pixel} = 4.2 \text{ microns}$$

- We will have to account for Multiple Fiducials (Sq-Rt of N); this would give 2.9 microns
- 2.9 microns **results in a 0.048 mm spacing error/ROC error**

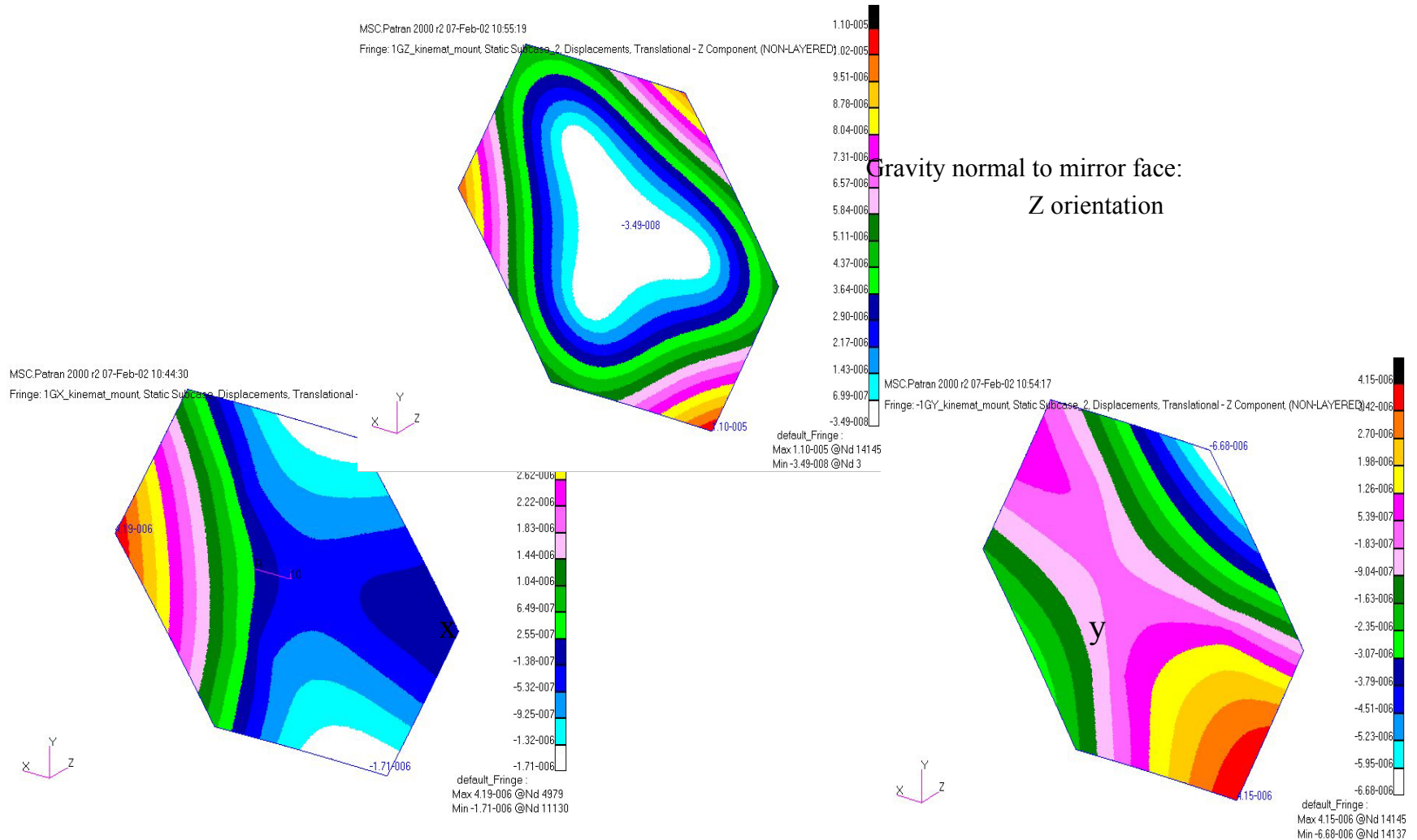
# Gravity Deflection

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- The following slides show Zernike coefficients for three gravity load cases (supplied by Larry Craig, NASA/MSFC)
- The mirror is kinematically supported at three points on the back
- The three images are Patran plots of the NASTRAN Z displacements (meters) caused by gravity deflection (small in-plane deformations will also exist)
- The deflections are decomposed into fringe Zernike coefficients

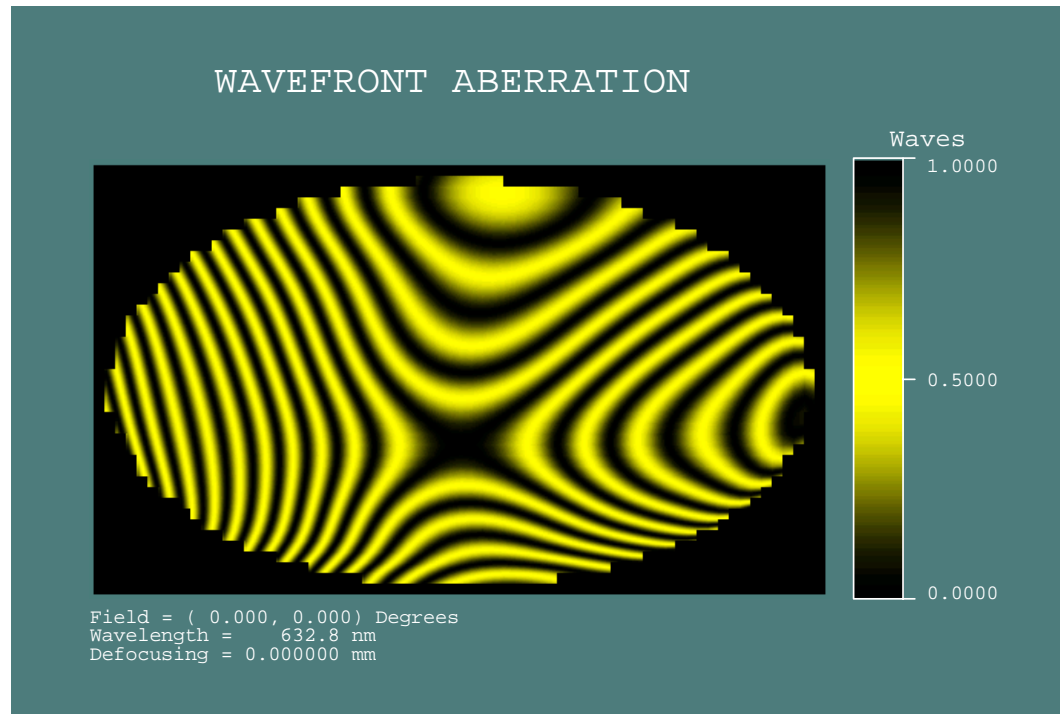
# Gravity Deflection Plots

(Supplied by: Larry Craig, NASA/MSFC)



# Power in Mirror due to Gravity -- Interferogram

**Estimated ROC through the Null System is  $-0.282$  mm**  
which is consistent with sag calculation



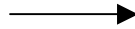
# List of Error Sources

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- Null
  - Focal Length measurement errors
  - Other symmetric mfg errors in the Null that convolve with power
  - Ability to process-out align. errors of Null rel. to interferometer
- Centroiding of the Fiducials with fringes in the way
  - Imaging of Fiducials through Null is poor (large caustic)
    - 50 microns RMS Spot Size (0.05 mm TA, OPD  $2\lambda_v$ )
    - However, large spots are desired for Centroiding
- Interferometer errors such as beam divergence
- Drift in stages that hold components
- Gravity errors on/of the mirror
- Fit of the Zernikes

# Top Level Error Budget

0.71 mm



ROC  
Error

0.71 mm



Systematic Error  
(1)

Random Error  
(Rapid Variation)  
(2)

Test Residual  
(3)

0.65 mm → Test Optics (1A)

0.28 mm → Gravity (1B)

Turbulence

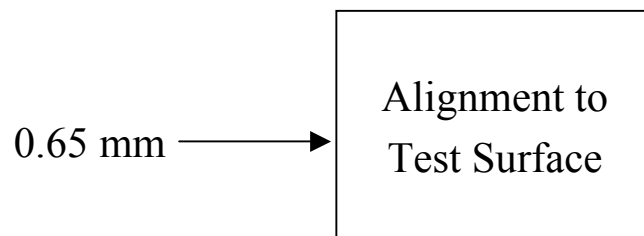
Noise

Vibration

Known residual of test piece  
(especially errors in conic)

# Alignment to Test Surface

1A3



Positioning of  
Test Surface  
1A3A

0.26 mm  
[e.g. Alignment Mix,  
or 0.086 mm of YDE]

Optical  
Registration  
of Fiducials  
1A3B

0.60 mm  
(See Next Pg)

Drift of Radius,  
Vertex of center,  
Effective Conic  
1A3C

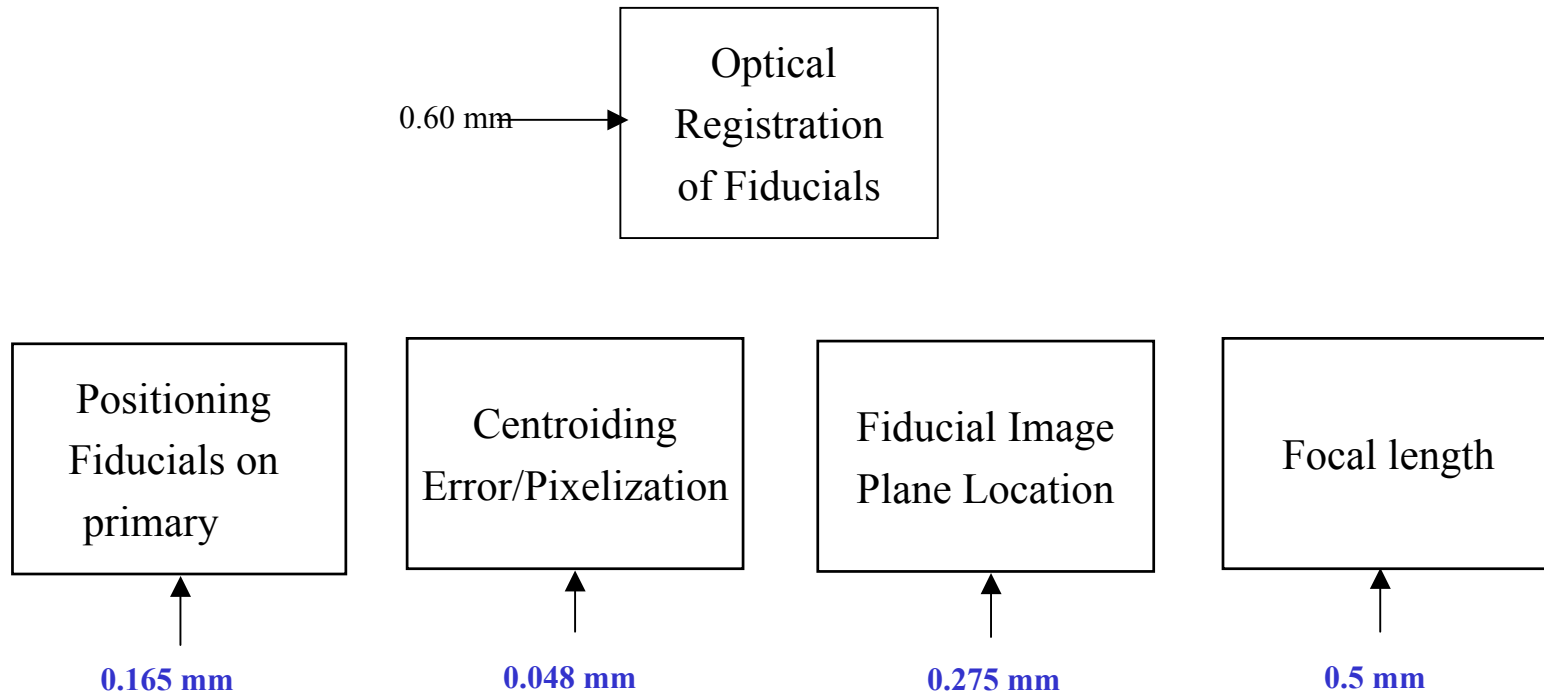
Drifts in primary, esp.  
Conic. Contrib. TBD.

Environmental  
1A3D

Stage drifts, x, y, z

# Optical Registration of Fiducials

1A3B



# Major Sources - Error Roll Up

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- **RSS for null positioning is: 0.59 mm**
    - focal length error
    - image plane location error
    - Fiducial separation
    - Centroiding/pixelization
  - **Gravity contribution: 0.282 mm**
  - **Decentration/tilt errors: 0.26 mm**
    - First Autocollimate off of Segment Ref. Flats to Limit Tilt
    - Centroiding of a Fiducial Can Be Used for Lateral Location
      - Absolute location accuracy again ties to FI knowledge (driver)
      - Location of Fiducial on Piece-Part also plays a role
    - 0.0014 mm YDE based purely on Optical Technique (and easier for Leica)
      - 0.11 mm of radius change
    - Amalgam Used (Conservative)
  - **RSS Error Rollup: 0.71 mm**
-

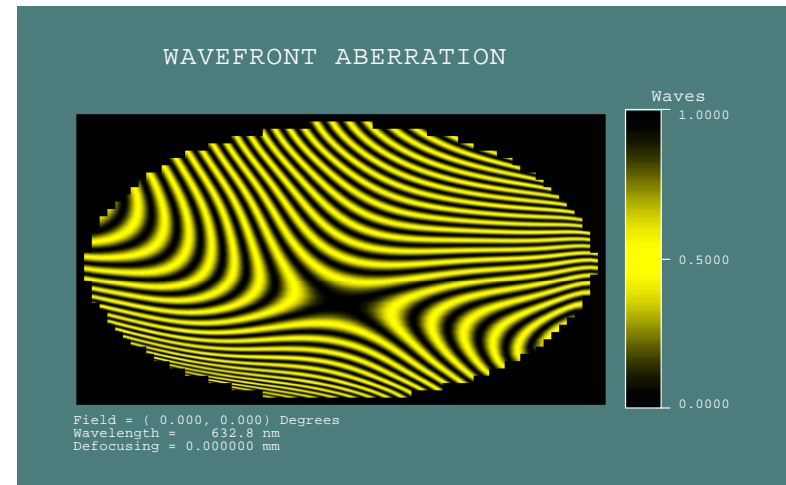
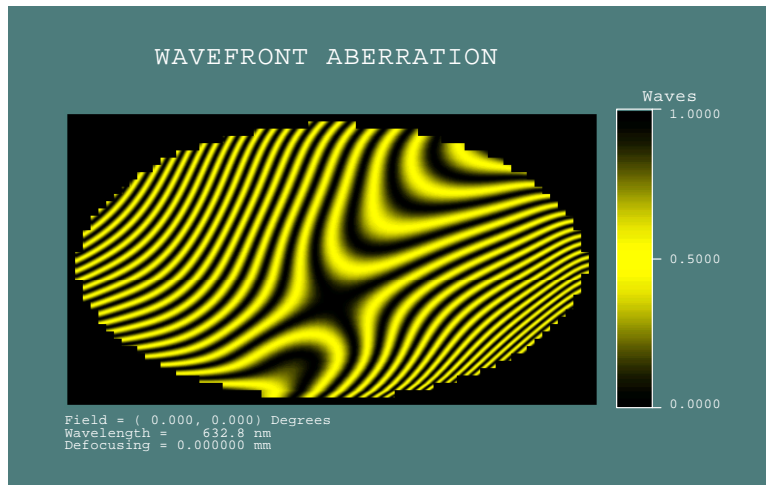
# A Simulation of an Interferogram From Error Roll Up

(Shows Aberrations Can be Captured in the Interferometer)

Tilts: ADE,BDE,CDE -> 0.0002, 0.0006, 0.01 deg

Decenter: XDE, YDE -> 0.125,-0.05 mm

- Null-Parabola mislocation: 0.6 mm
- ROC error 0.6 mm
- ~ 24 waves P-V
- Null-Parabola mislocation: -0.6 mm
- ROC error -0.6 mm
- ~ 22 waves P-V



# Reality Check



- Place interferogram at the exit pupil of an unperturbed system
- Include effects of tilts and decenters (See Pg 33):
  - Tilts: ADE,BDE,CDE  $\rightarrow$  0.0002, 0.0006, 0.01 deg
  - Decenter: XDE, YDE  $\rightarrow$  0.125 , -0.05 mm
- Include effect of gravity
- **Use CODE V to Optimize on the Primary's ROC**
  - **Null-parabola mislocated +0.6 mm, predicted ROC  $\Delta$  of 0.75 mm**
  - Null-parabola mislocated -0.6 mm, predicted ROC  $\Delta$  of - 0.58 mm
  - **ROC changed to -10001 mm with other perturbations present**
- **CODE V predicted - 0.81 mm Change in ROC, a good match**

# **The ROC Calibration Approach Has Been Anchored & Gives $< 1$ mm Error**

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- **A similar Null FL calibration was used on the Hubble First Servicing Mission on the Corrective Optics for NICMOS and for the aspheric corrector with WFPC**
- A similar approach to measuring Null Fl has also been used at CommOptics
- Fiducial Centroiding Algorithms match measured data
- **The Purely Optical Means to Locate the Null is New, But Works to Adequate Tolerance Levels on the Computer. It can be supplemented by mechanical means and/or by distance measuring interferometry**